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ACOUSTIC MEASUREMENTS IN SUPERSONIC TRANSITIONAL BOUNDARY LAYERS

S. R. Pate and M. D. Brown

ARO, Inc.

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NOTICES

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Project 8953, Task 03.

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This technical report has been reviewed and is approved.

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ABSTRACT

Surface pressure fluctuations associated with transitional and turbulent boundary-layer flows on a sharp, slender cone at supersonic Mach numbers have been experimentally investigated in the AEDC-VKF Tunnel A 40- by 40-in. supersonic wind tunnel using a flush-mounted 0.25-in.-diam microphone. The results at Mach numbers 3 and 4 demonstrate the feasibility of locating microphones onboard wind tunnel test models to measure overall pressure fluctuations and power spectral distributions in transitional and fully developed turbulent flows. Transition Reynolds numbers determined using a surface microphone are compared with two other established methods of detection. Selected boundary-layer pressure fluctuation characteristics (power spectral density and root-mean-square values) and transition profiles are presented. Methods of data acquisition and analysis are discussed.

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NOMENCLATURE

b	Nose bluntness, in.
$F(\omega)$	Power spectral density, $(\text{psi})^2$/radians/sec
f	Frequency, Hz
ℓ	Axial location, in.
M_δ	Local free-stream Mach number
M_∞	Tunnel free-stream Mach number
p	Surface probe total pressure, psia
p_o	Tunnel stilling chamber total pressure, psia
p_o'	Tunnel free-stream total pressure downstream of a normal shock wave, psia
$\tilde{p}$	Root-mean-square of surface pressure fluctuations, psia
p_∞	Free-stream static pressure, psia
q_δ	Local free-stream dynamic pressure, psia
q_∞	Tunnel free-stream dynamic pressure, psia
$(\text{Re/in.})_\delta$	Local free-stream unit Reynolds number per inch $\left[(\text{Re/in.})_\delta = U_\delta/\nu_\delta\right]$
$(\text{Re}_t)_\delta$	Transition Reynolds number based on local flow properties, $\left[(\text{Re}_t)_\delta = U_\delta x_t/\nu_\delta\right]$

U_δ	Local velocity, in./sec
V_{rms}	Root-mean-square voltage fluctuation, volts
x	Surface location, in.
x_t	Surface location of transition, in.
δ	Boundary-layer velocity thickness, in.
δ^*	Boundary-layer displacement thickness, in.
θ_c	Cone half-angle, deg
ν_δ	Local kinematic viscosity, in.^{2}/sec
Φ	Power spectral density, psia^2/Hz or v^2/Hz $\left[\tilde{p}^2 = \int_0^\infty \Phi df\right]$
ω	Angular frequency, radians/sec

SECTION I
INTRODUCTION

The boundary-layer transition process has defied the development of a successful theoretical analysis for over six decades. Consequently, the bulk of knowledge accumulated on this extremely important but equally complex fluid flow phenomenon has relied almost 100 percent on experimental data. The importance of the transition process is particularly emphasized at supersonic and hypersonic speeds where numerous aeronautical problems, such as friction drag, heat transfer, wake structure, flow separation, internal noise, and structural fatigue failure, are associated with high-speed viscous flows. In general, the aerodynamic characteristics exhibited by these problems are directly related to the state of the boundary layer (laminar or turbulent) and, consequently, indirectly to the location of boundary-layer transition. The optimum design of many high-speed, high-performance vehicles is dependent on adequately defining the boundary-layer transition process with its inherent increases in mass and momentum transfers.

Extensive and detailed experimental investigations of the boundary-layer transition phenomenon have been underway at the Arnold Engineering Development Center (AEDC), von Kármán Gas Dynamics Facility (VKF) for more than a decade (Refs. 1 through 5). These studies have been directed toward defining and evaluating, qualitatively and quantitatively, the many parameters that are known to influence the transition location and process.

Various methods for detecting the transition location and providing information on the transition process have been used with varying degrees of success (Refs. 1 through 11). Steady-state measurements of impact pressure, surface temperature, surface shear stress, and boundary-layer growth through the transition region have been reported in Refs. 1 through 6. The hot-wire anemometer (Refs. 5, 7, and 8) has proven to be an invaluable instrument for studying the transition process at both subsonic and supersonic speeds. The use of thin films to measure heat-transfer fluctuations at supersonic speeds has recently been successful (Ref. 9). Optical methods (Refs. 5 and 10), as well as visual observation of thermal sensitive paints (Ref. 11), have also contributed experimental data on the transition process. All of these various and varied methods of detection have made individual contributions to the understanding of the transition process, and results from some of the methods have been correlated to provide a more complete picture. However, there is no single instrument or measuring technique that has provided data sufficient for a complete understanding of the transition process.

This report presents a small portion of recent boundary-layer transition results obtained at AEDC-VKF and describes the use of a flush-mounted surface microphone for measuring the location of transition, determining the region of transition from beginning of onset to fully developed turbulence, and as an instrument for providing additional valuable information on the transition process at supersonic speeds. Selected surface pressure fluctuation data, root-mean-square (rms) levels and power spectral density distributions, obtained in laminar, transitional, and fully turbulent flow on a slender cone at Mach numbers 3 and 4 are presented and discussed.

SECTION II
EXPERIMENTAL ENVIRONMENT

2.1 WIND TUNNEL FACILITY

Tunnel A (Gas Dynamic Wind Tunnel, Supersonic (A)) is a continuous, closed-circuit, variable density wind tunnel with an automatically driven flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel can be operated at Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R ($M_\infty = 6$). Minimum operating pressures range from about one-tenth to one-twentieth of the maximum at each Mach number.

2.2 TEST MODEL AND APPARATUS

The test model (Figs. 1, 2, and 3, Appendix) was a 10-deg total angle, stainless steel cone equipped with a tool steel nose section. The model had a surface finish of approximately 10 μin. and a tip total bluntness between 0.005 and 0.006 in. A model length of 49.05 in. was obtained by connecting three individual sections (nose, middle, and aft) as illustrated in Figs. 1 and 2. In order to maintain a perfect joint between the sections, the model surface was refinished after attaching each model section.

Model instrumentation included four surface static pressure orifices, two surface thermocouples, and one flush-mounted 0.25-in.-diam microphone. Specific instrumentation locations are provided in Fig. 1. Figure 4 provides a sketch illustrating the method of microphone installation.

Pressure data were also obtained using a longitudinally traversing surface probe as illustrated in Figs. 2 and 3. Surface probe measurements provide a well-established method for determining the location of transition. The surface probe was remotely controlled and electrically driven and provided a continouous trace of the probe pressure on an X-Y plotter from which the location of transition was determined.

SECTION III
DYNAMIC PRESSURE INSTRUMENTATION

3.1 MICROPHONE

The transducer employed to measure the cone surface pressure fluctuations consisted of a Brüel and Kjar, Model No. 4136, 0.25-in.-diam condenser microphone mounted as illustrated in Fig. 4. The microphone cartridge, when connected to Brüel and Kjar types UA0122 flexible adapter and 2615 cathode follower, and powered by a Brüel and Kjar type 2801 power supply, has an atmospheric pressure frequency response of from 30 Hz to 70 kHz and a dynamic pressure range of from 70 to 180 db(re = 0.0002 microbars).

Since the air mass inside the cartridge is used to provide critical damping for a flat frequency response at 1 atm of pressure, the microphone has a resonant peak in its frequency response curve when operated at ambient pressures lower than 1 atm. Figure 5 shows the change in sensitivity versus frequency at a pressure of 300 mm Hg. This curve was obtained using Brüel and Kjar type 4142 calibration apparatus. A Fourier analysis of tunnel data (Fig. 6) shows the effect of the microphone's resonance when operated at a low pressure and exposed to wideband fluctuating pressures. The output signals centered about the resonant frequency will cause errors in the rms values of the fluctuating pressure. To reduce these errors, frequencies above 25 kHz were filtered out of the tunnel data with a filter having a 12-db/octave roll-off.

3.2 RECORDING AND ANALYZING EQUIPMENT

The output of the microphone was fed through a Spencer-Kennedy Laboratories, Inc., Model 302 variable electronic low pass filter to a Brüel and Kjar type 2409-rms voltmeter. The rms values of pressure fluctuations were read directly on-line from the voltmeter, and the time-varying pressure fluctuations, using the voltmeter's amplifier as a pre-amplifier, were recorded on an Ampex Model FR1300 analog tape

recorder for posttest data analysis and for verification of the on-line rms values. The data were recorded simultaneously on a direct and an FM channel having frequency responses of from 300 Hz to 300 kHz and direct current to 20 kHz, respectively.

For analysis, loops were made from the data tapes, and the recorded signals were played back into a Technical Products Model TP-625 spectrum analyzer. Power spectral density analyses were made from the recorded data using a 10-Hz bandwidth filter and covering a frequency range from 10 Hz to 20 kHz. Figure 7 shows the block diagram for the dynamic pressure recording and analyzing system.

3.3 CALIBRATION PROCEDURE

The voltage versus pressure characteristic of the microphone was obtained by applying known pressure levels to the microphone and recording the voltage output from the filter. This calibrates the filter and microphone as a single unit. Known pressure levels were generated using an oscillator, a power amplifier, a horn driver, and a standard microphone. Using a frequency of 250 Hz, the pressure levels were set with the standard microphone and then transferred to the working microphone. The resulting calibration curve is shown in Fig. 8. Since the sensitivity of a microphone is usually listed in decibels, appropriate scale factors were used to convert the sound pressure levels to pounds per square inch.

SECTION IV
DISCUSSION OF RESULTS

4.1 TRANSITION DETECTION

Presented in Fig. 9 are the surface pressure fluctuations ($\tilde{p}/q_\infty$) measured with the microphone at station 45.5 in. for Mach numbers 3 and 4. These data show a low $\tilde{p}/q_\infty$ value to exist when the boundary layer was laminar over the entire model surface followed by a very sharp peak and then rapid decay with increasing p_o or $(Re/in.)_\delta$, as transition moved forward and the sensor was exposed to fully developed turbulent flow. The finite $\tilde{p}/q_\infty$ levels that existed when the flow was laminar are believed to be the direct result of the noise level that radiates from the tunnel wall turbulent boundary as reported in Refs. 1 and 2.

Data as presented in Fig. 9 in terms of rms alone can be misleading, as has sometimes occurred in the literature, when one is not aware of the limitations imposed by the microphone or data recording system frequency range. The absolute values of the fluctuating pressure profile expressed as $\tilde{p}$ and Φ are presented in Fig. 10 for $M_\infty = 3$. These data, as shown in Fig. 10a, more clearly indicate the relation of the absolute levels of the pressure fluctuation when the flow was laminar, transitional, or turbulent. Four selected data points, designated points A, B, C, and D, have been analyzed, and their spectral distributions are shown in Fig. 10b. As discussed in the preceding section, a 25-kHz filter was installed to eliminate the microphone resonance effects at frequencies above 25 kHz. The spectral distributions presented in Fig. 10b show that a significant amount of the overall rms data in Figs. 9 and 10a was not recorded for test points C and D. Based on the results of Refs. 12 and 13, it can be estimated that frequencies up to approximately 200 to 300 kHz are present in the cone turbulent flow. Consequently, the turbulent $\tilde{p}$ data $(Re/in.)_\delta \gtrsim 0.15 \times 10^6$) presented in Figs. 9 and 10a are significantly lower than a true total overall rms would indicate.

The sharp peak in the rms profiles or $\tilde{p}/q_\infty$ profiles suggests that the microphone is an excellent indicator of transition. This conclusion is verified by comparing the rms transition profiles with transition profiles obtained in this study using a longitudinally traversing surface pressure probe and recently published data (Ref. 9) obtained with a thin film.

Thin-film gages differ from acoustic sensors in that they respond to fluctuations in the turbulent heat-transfer rate rather than the turbulent pressure fluctuations, although the two are directly related. The thin-film data from Ref. 9 are shown in Fig. 11 for comparative purposes with the $\tilde{p}$ data in Figs. 9 and 10a. The similarity in the profiles and very sharp overshoot in the region of transition is quite evident. Thus, it can be concluded that a surface microphone rms pressure fluctuation will produce transition profiles similar to thin-film voltage fluctuations. Presented in Fig. 11a are typical pressure traces obtained when the surface probe was traversed along the surface. These data also indicate the regions of transition, although the pressure overshoot or peak was, in general, not as pronounced as the microphone rms signal.

The peak point in the rms pressure fluctuation was selected to define the point of transition (it should now be clear to the reader that the transition process occurs over a finite length rather than instantaneously at a specific location). Transition Reynolds numbers for $M_\infty = 3$ and 4, as

defined by the peak locations in the rms pressure fluctuation profile and the surface probe pressure trace, are presented in Fig. 12. Also included in Fig. 12 are transition data obtained from viewing shadowgraph photographs. Figure 12 clearly establishes that the location of transition as determined by a surface microphone is consistent with the accepted pitot and shadowgraph values. Additional information on the subject of transition and the use of the pitot probe and other methods of detection can be found in Refs. 1 through 10.

Figure 13 presents a replot of the spectral data in Fig. 10b to more clearly show certain pertinent features. The spectra of the laminar flow profile (A) (tentatively suggested to be directly related to the tunnel radiated aerodynamic noise levels, Refs. 1 and 2) are more clearly illustrated. Also evident is the concentration of energy present in the transition profile (B) at the lower frequencies ($f < 1000$). The exact source of the low frequencies associated with the transition process is not completely understood at this date, but they are tentatively believed to be aerodynamic and not structurally generated. Figure 14 presents photographs of the oscilloscope record showing the time-dependent microphone pressure fluctuation output for the selected data points A, B, C, and D, plus a fully laminar point, $(\mathrm{Re/in.})_\delta = 0.054 \times 10^6$.

The ability of the flush-mounted microphone to measure the unsteady and mean values of the transition process at supersonic speeds is clearly illustrated in Figs. 9 through 14. These results indicate the utility of the microphone to provide valuable information on the transition process at supersonic Mach numbers.

4.2 OVERALL LEVELS AND POWER SPECTRAL DENSITY

In addition to influencing flight performance, the state of the boundary layer also has significant bearings on the internal noise levels and structural fatigue failure of future high-speed aircraft. Computation of the fuselage response and internal noise field requires a knowledge of the overall fluctuating pressure levels and the power spectrum.

Pressure fluctuations, rms values, obtained at subsonic velocities in fully developed turbulent flow have been shown to correlate independent of Mach number when nondimensionalized by the dynamic pressure (Ref. 14). Lowson in Ref. 12 has extended this correlation to supersonic speeds and demonstrated a significant Mach number effect, as exhibited by the data in Fig. 15 taken from Ref. 12. One general procedure for estimating overall sound pressure levels is to obtain a $\widetilde{p}/q_\delta$ value from Fig. 15, or a similar plot, and estimate maximum $\widetilde{p}$ at the maximum q_δ

to be experienced. The transitional $\tilde{p}/q_\delta$ values obtained in this investigation (Fig. 9) are included in Fig. 15 for M_∞ = 3 and 4. These preliminary results indicate that pressure fluctuation levels in the transition region can exceed the turbulent values by one to two orders of magnitude. The significance of the result, although preliminary in nature, is quite evident. Since the transitional $\tilde{p}$ values (as are the turbulent flow values) are Mach number, Re/in., and configuration dependent, future aircraft and missiles can be expected to require experimental programs designed to investigate these very high $\tilde{p}$ levels. These results have shown that the small (0.25- or 0.125-in.) flush-mounted microphone can be successfully employed to obtain these measurements in the supersonic Mach number range.

The nondimensionalized power spectral density of wall pressure fluctuations for the fully developed turbulent flow profile (Profile D, Figs. 10 and 13, $(Re/in.)_\delta = 0.64 \times 10^6$) is presented in Fig. 16 as a function of the Strouhal number ($\omega\delta^*/U_\delta$), for example, see Ref. 15. The agreement between the present data and data from Ref. 13 leads to the conclusion that small microphones can be located on board small test models and successfully used to measure turbulent pressure fluctuations at supersonic speeds.

SECTION V
CONCLUDING REMARKS

It has been shown that the flush-mounted surface microphone can be used successfully for accurately locating boundary transition and for experimentally investigating the transition region at high supersonic speeds. These results, obtained at Mach numbers 3 and 4 on a sharp, slender cone, have demonstrated the feasibility of locating small microphones on board wind tunnel test models to measure overall pressure fluctuation levels (rms) and power spectral distributions in transitional and fully developed turbulent flows. Results presented indicate that maximum surface pressure fluctuation intensities may not necessarily occur in fully developed turbulent flow at the maximum dynamic pressure but can be associated with the large pressure fluctuation overshoot which has been shown to be related to the transition process.

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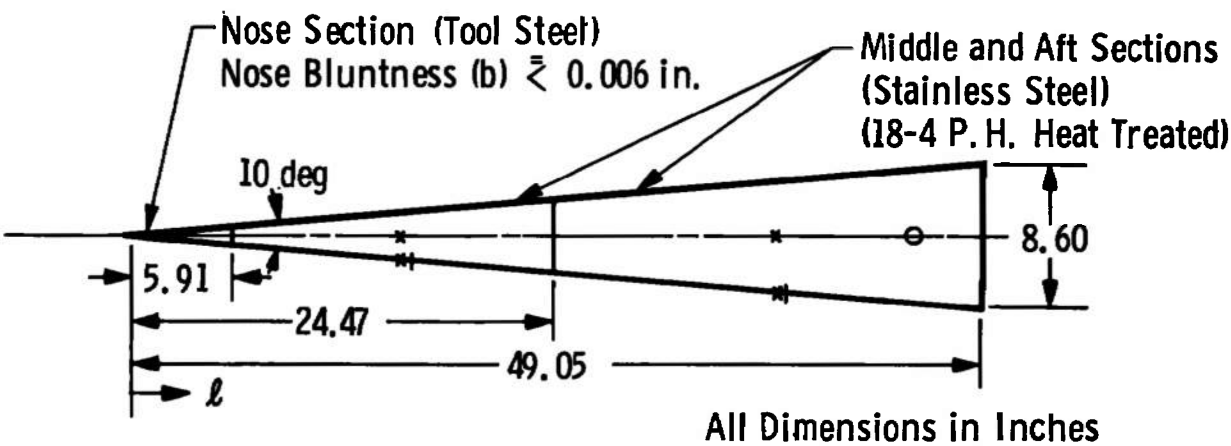
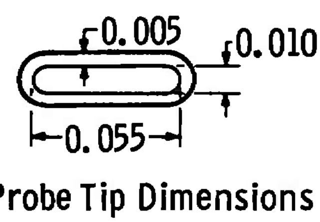
APPENDIX
ILLUSTRATIONS





Model Instrumentation			
Sym	Type	Quantity	ℓ, in.
x	Pressure Orifice, (0.020-in.-diam)	4	15.53, 37.12 (90 deg Apart)
I	Thermocouple	2	16.02, 37.61
o	Microphone	1	45.33

Fig. 1 Model Geometry

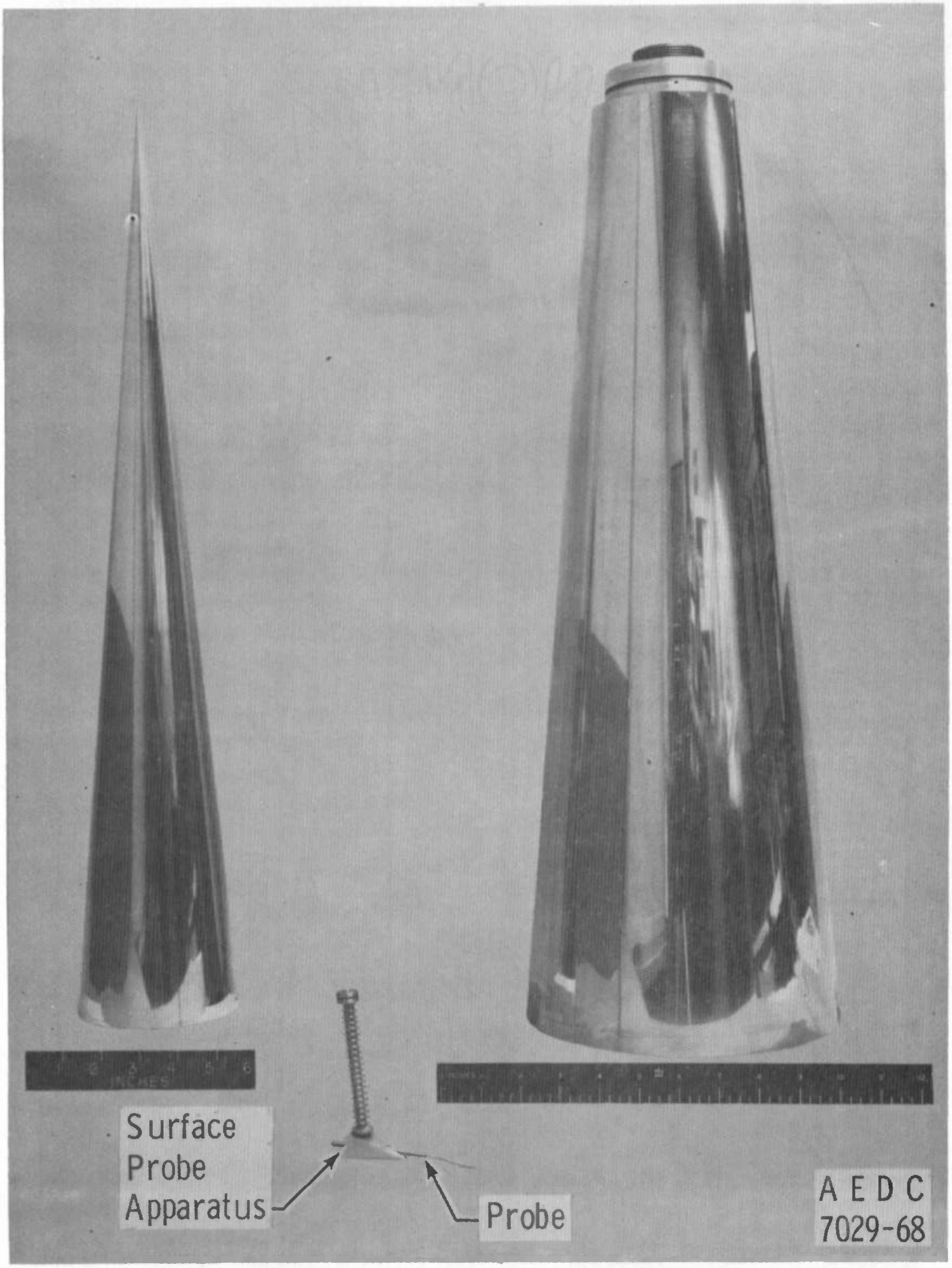


Fig. 2 Photograph of Model Components

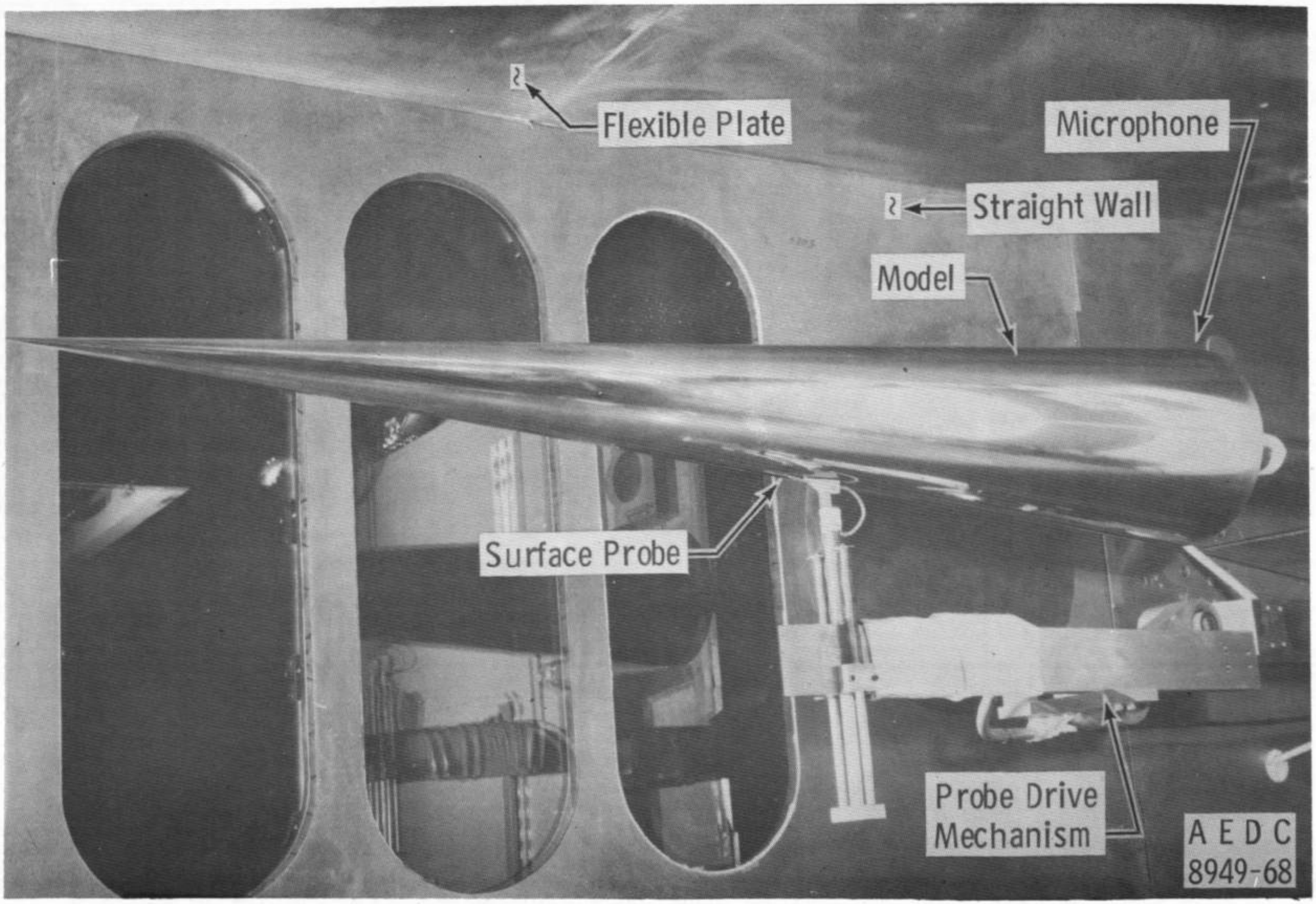


Fig. 3 VKF Tunnel A Cone Model Installation

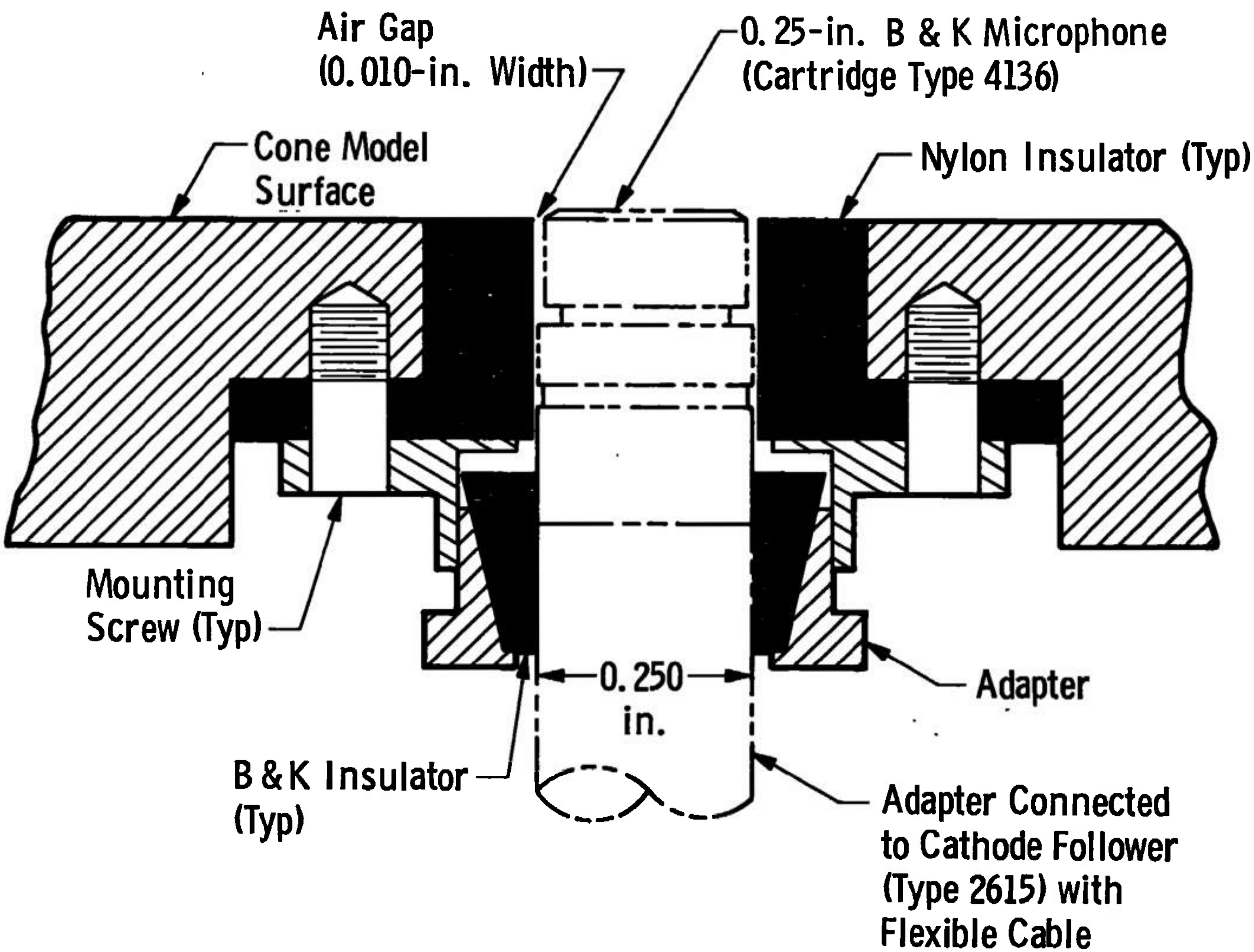


Fig. 4 Cutaway View Illustrating Microphone Installation

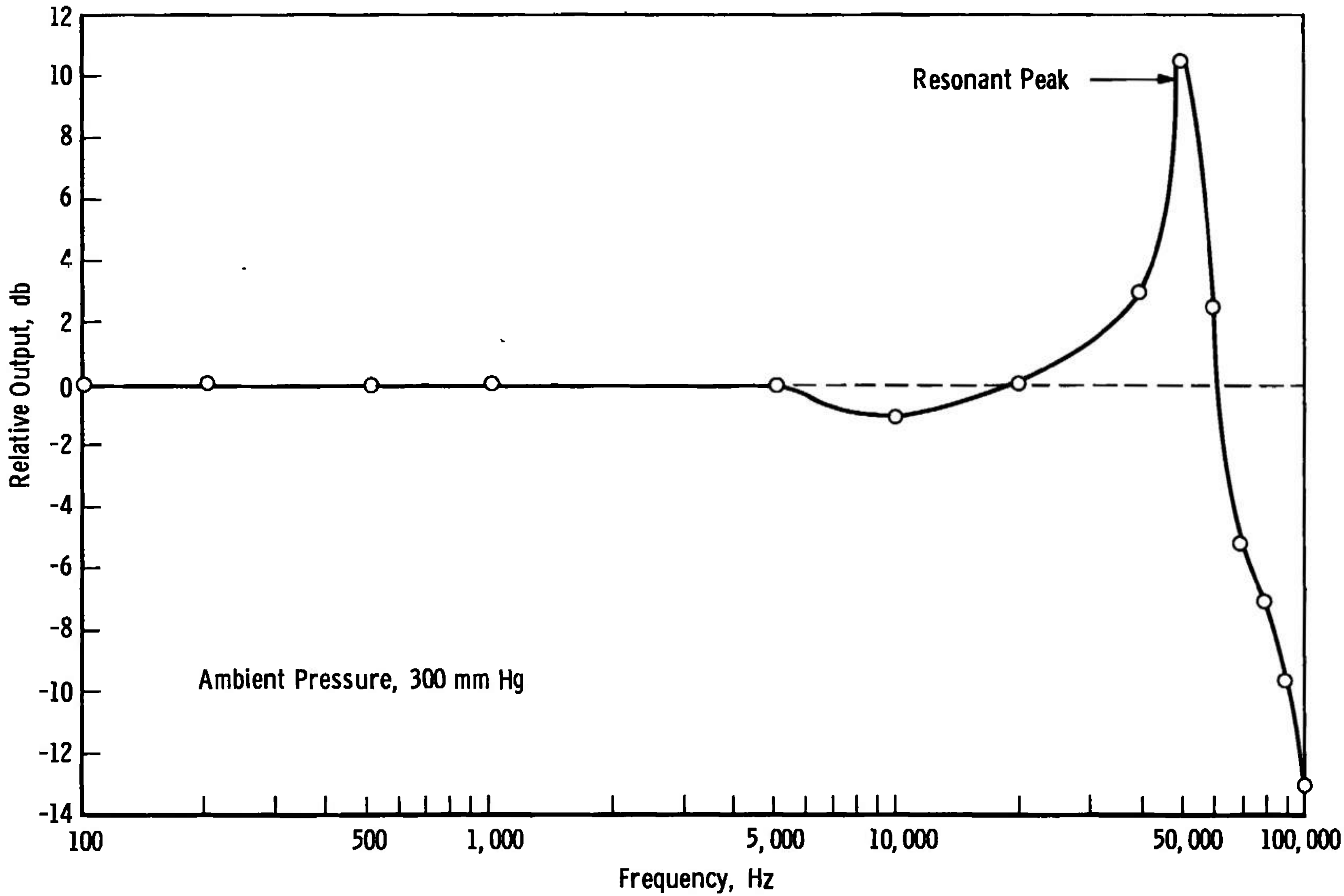


Fig. 5 Microphone Frequency Response

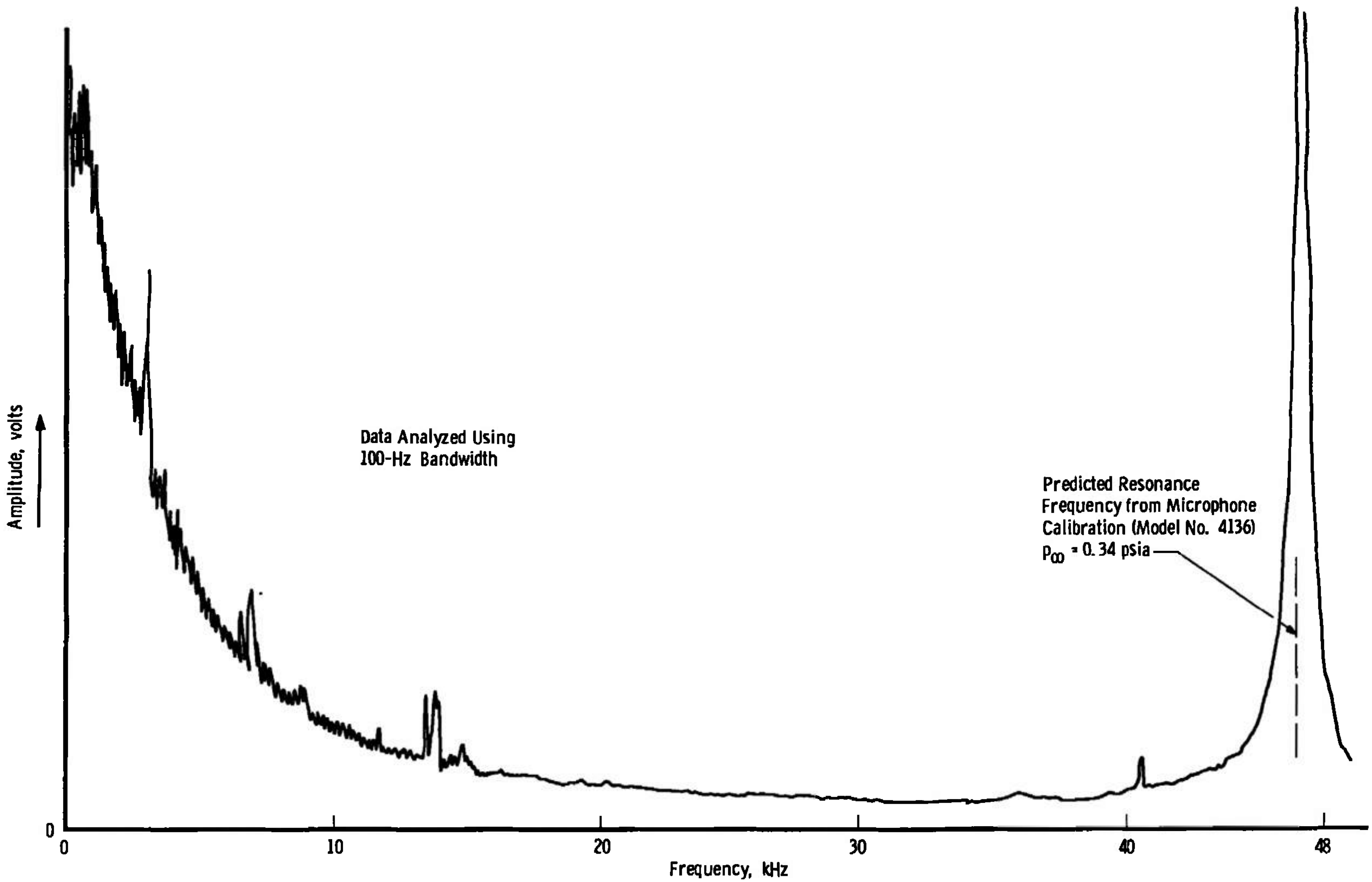


Fig. 6 Ambient Pressure Effects on Microphone Frequency Response, $M_\infty = 3$

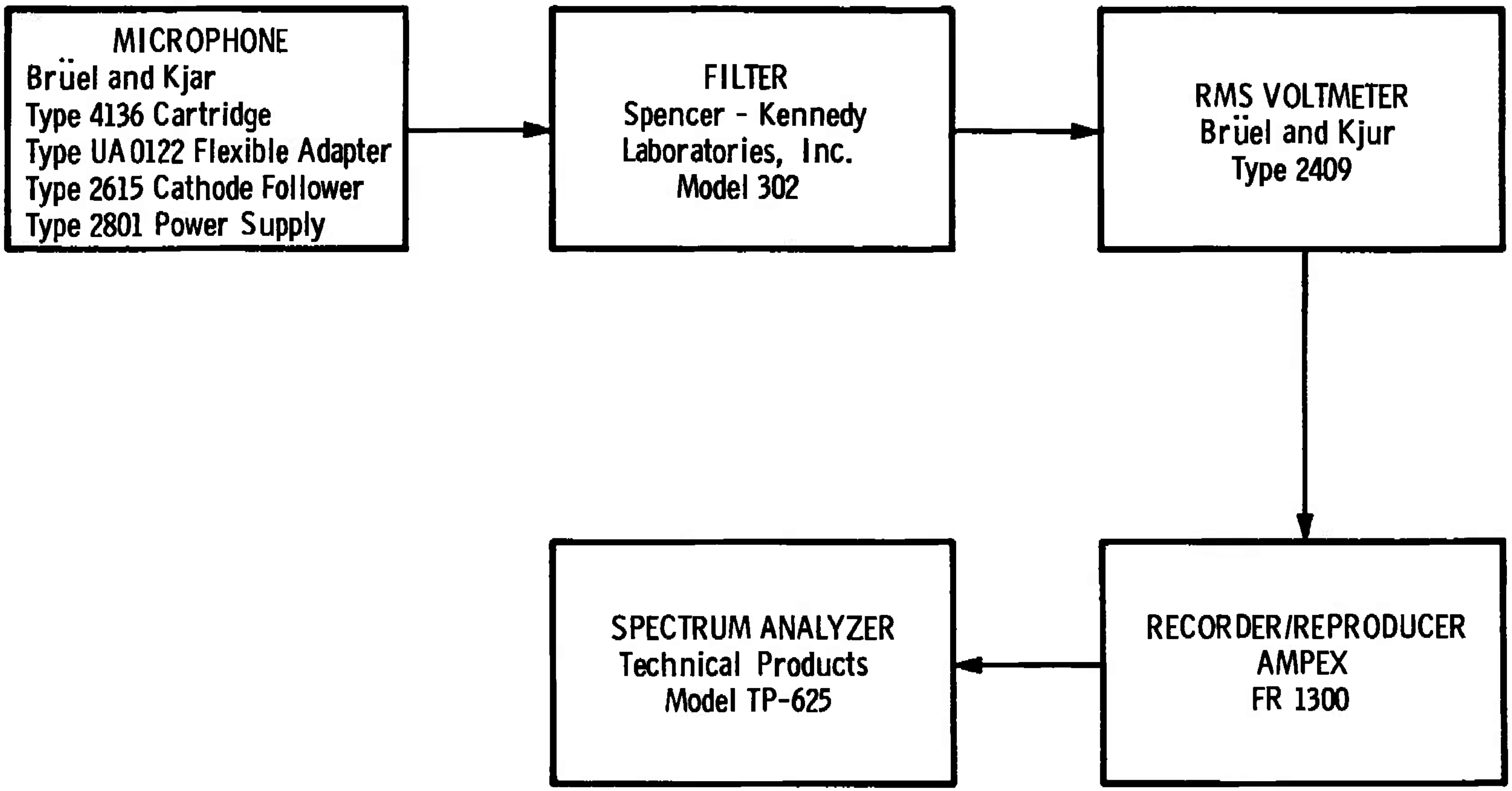


Fig. 7 Dynamic Pressure Recording and Analyzing System

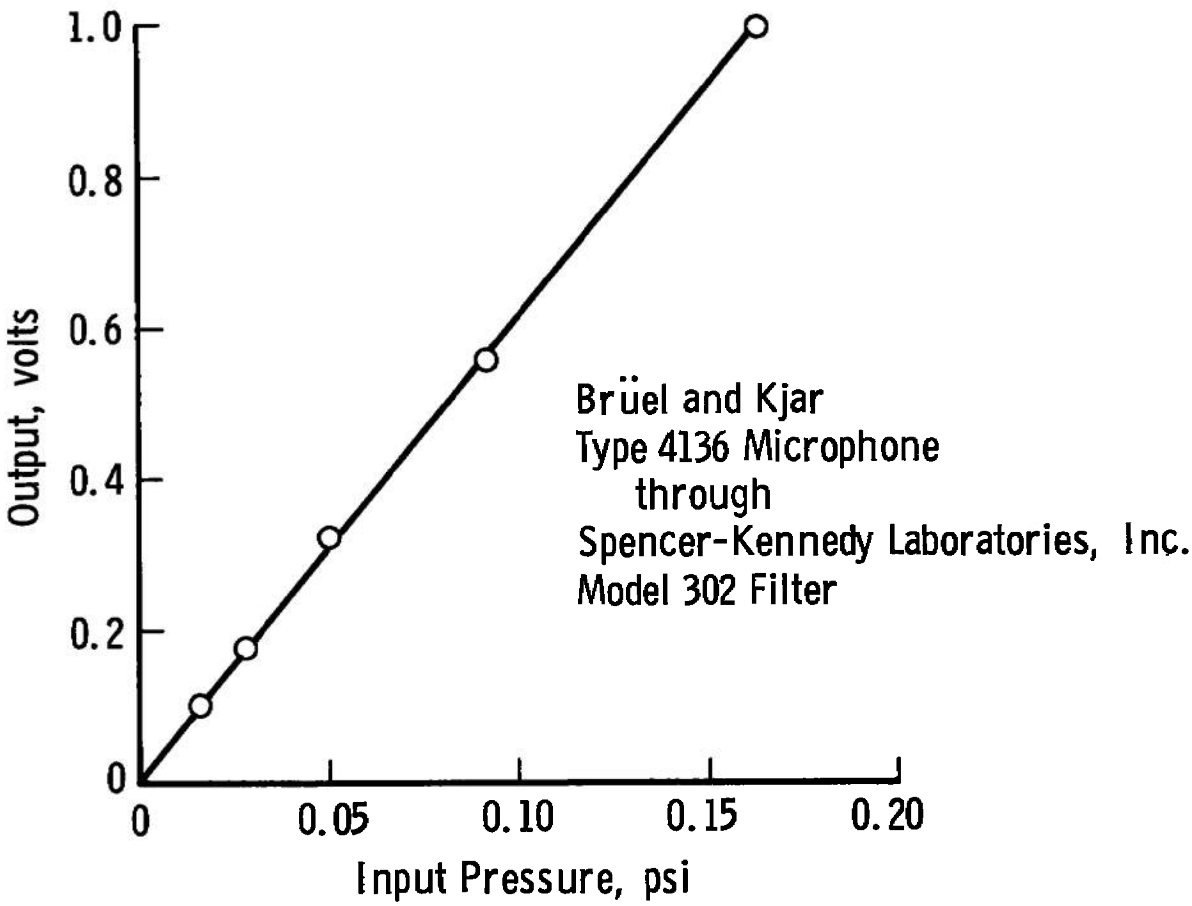
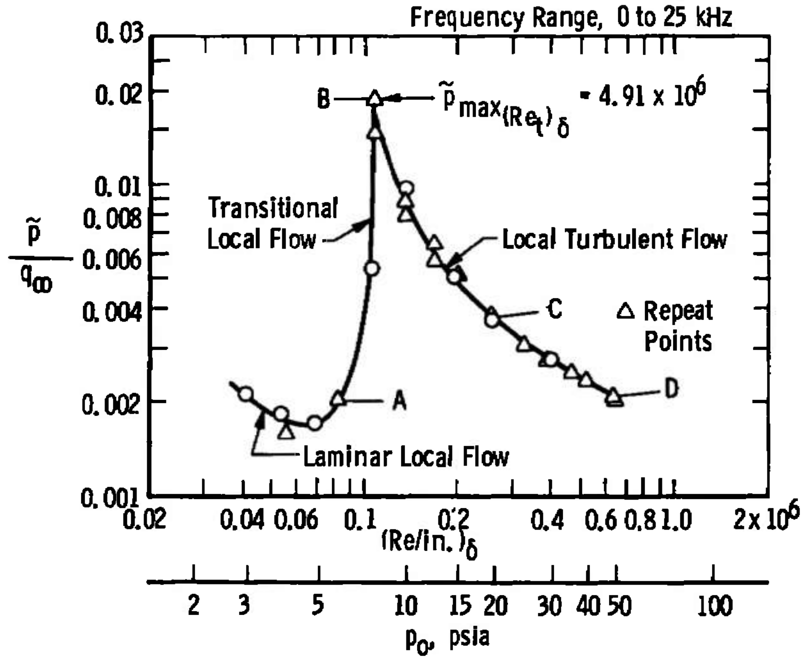
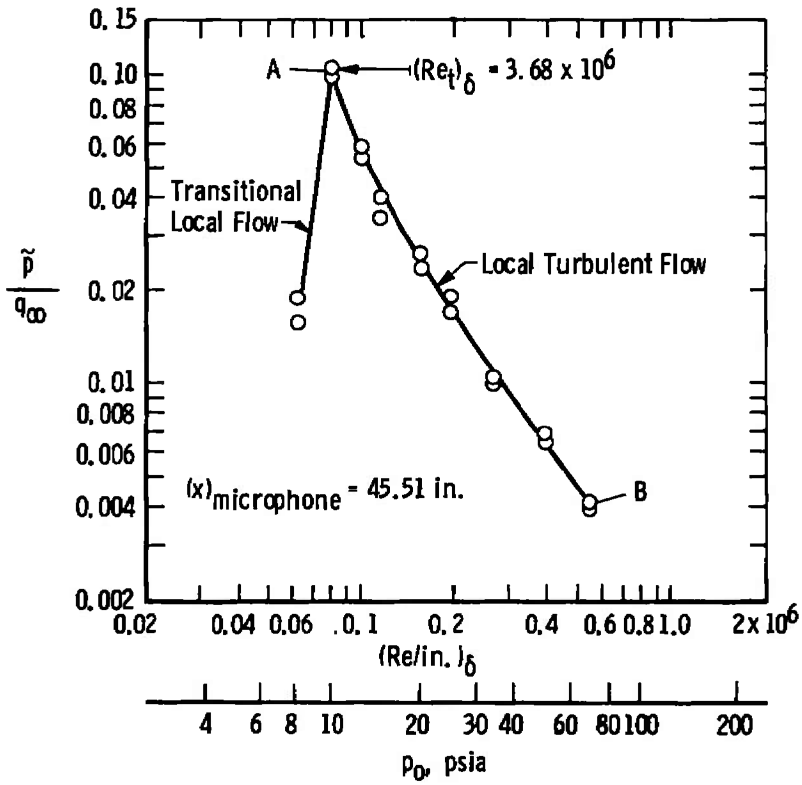


Fig. 8 Microphone Transfer Characteristics

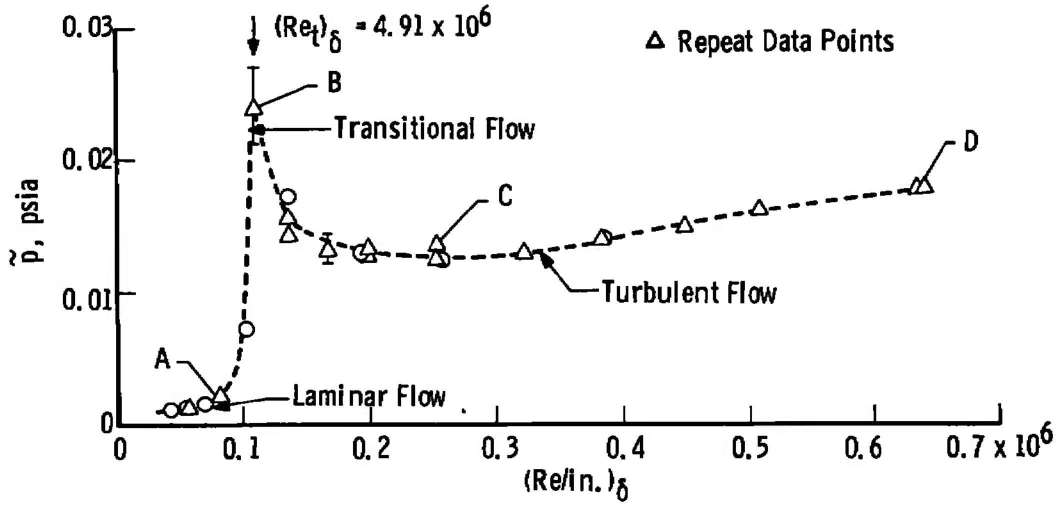


a. M_∞ = 3.0

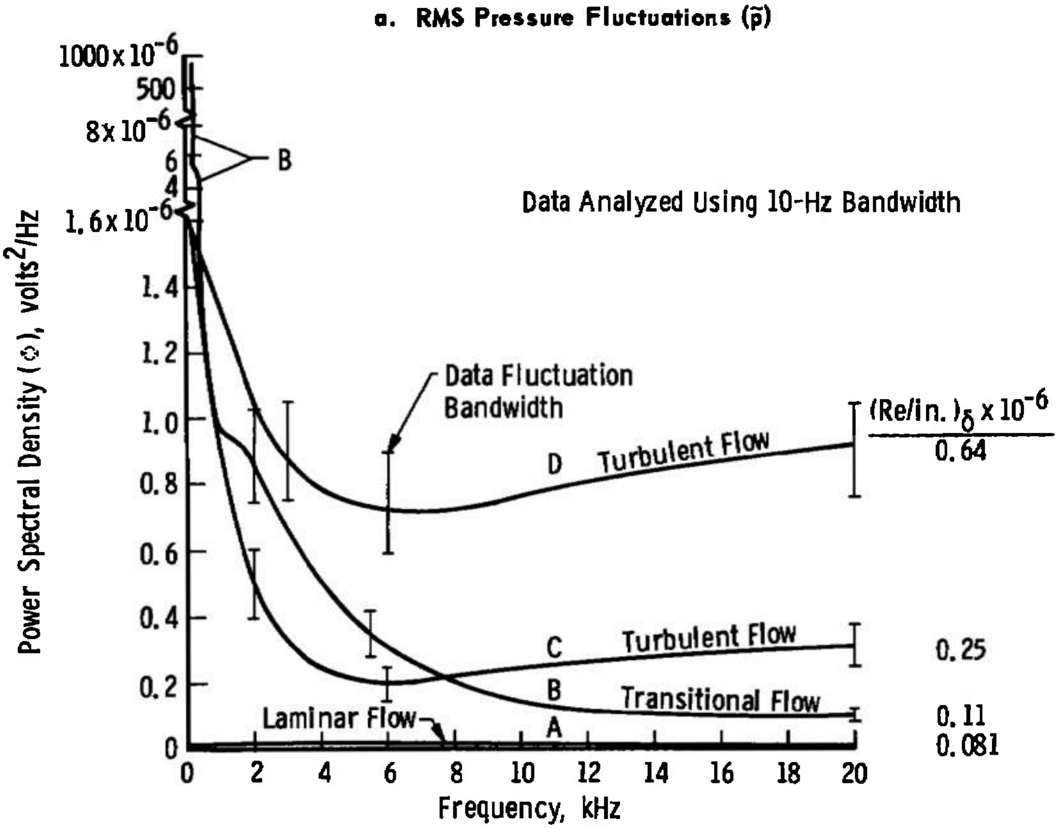


b. M_∞ = 4.0

Fig. 9 Detection of Transition from Microphone Root-Mean-Square Pressure Fluctuations, M_∞ = 3.0 and 4.0

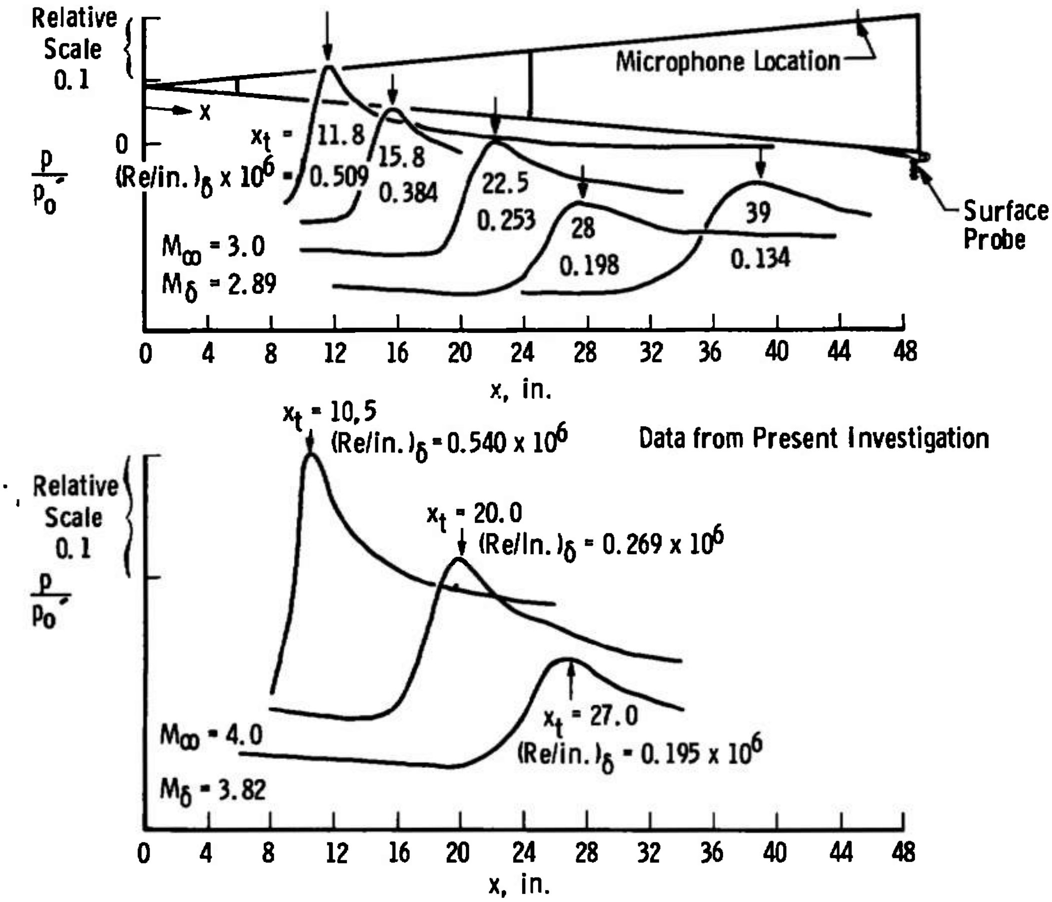


a. RMS Pressure Fluctuations ($\tilde{p}$)

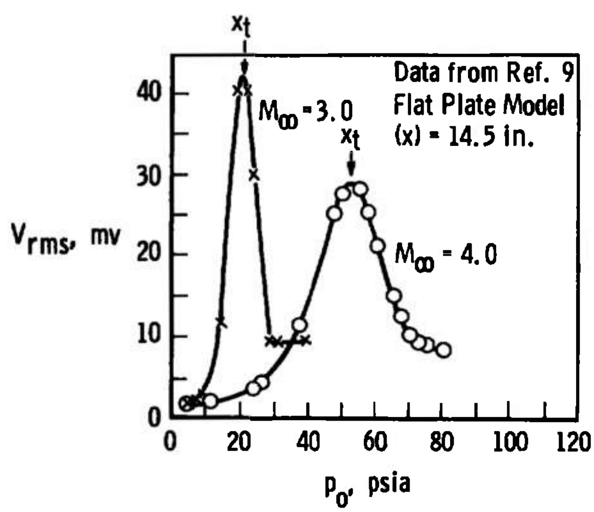


b. Spectral Distribution

Fig. 10 Microphone Results, $M_\infty = 3$



a. Surface Probe Transition Profile Traces



b. Thin-Film Transition Profile

Fig. 11 Examples of Surface Probe and Thin-Film Transition Profiles

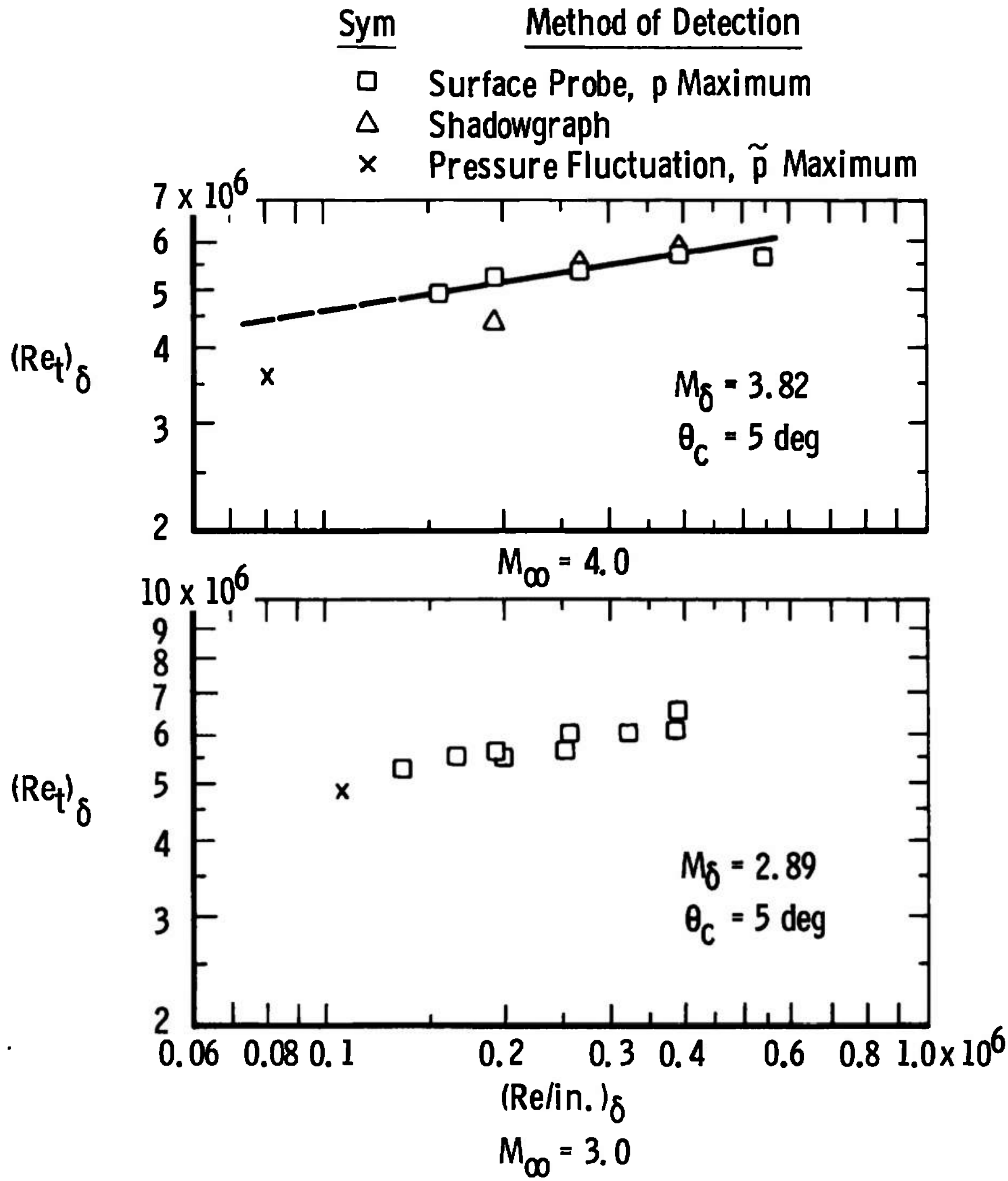


Fig. 12 Transition Reynolds Number Data from the AEDC-VKF Tunnel A, Sharp Cone

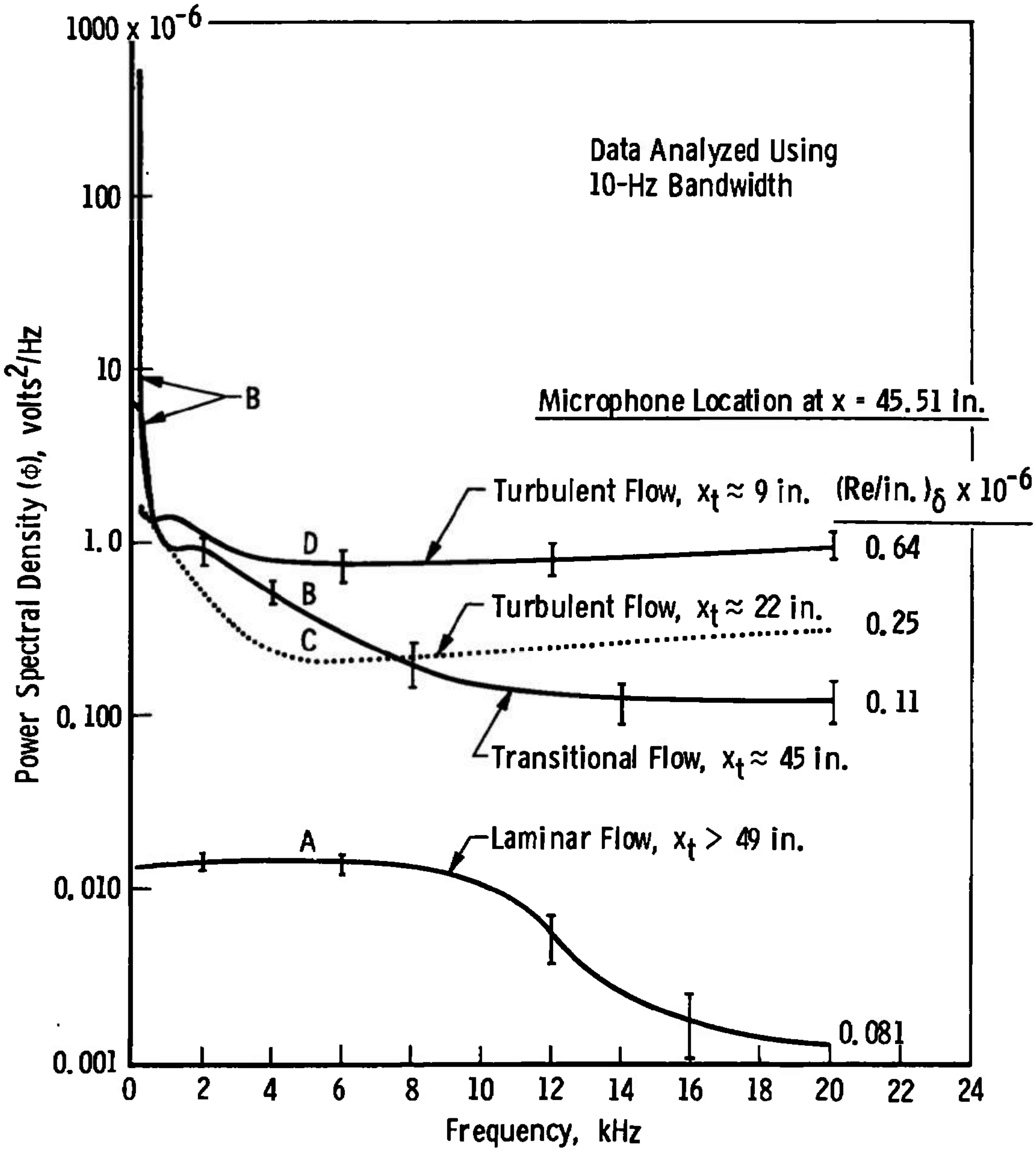
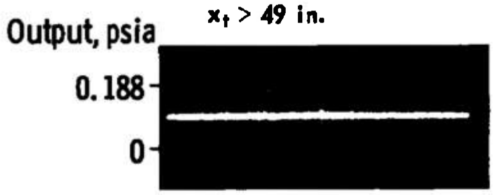


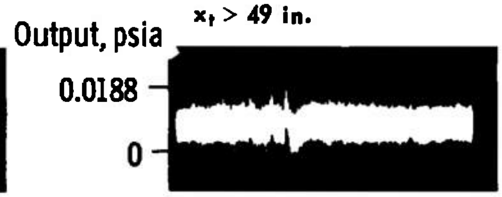
Fig. 13 Variation of Acoustic Spectra with Boundary-Layer State, $M_\infty = 3$

a. Laminar Flow,
(Re/in.)$_\delta$ = 0.054 × 10^6,
x_t > 49 in.

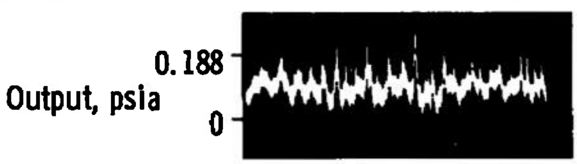
b. Laminar Flow,
(Re/in.)$_\delta$ = 0.054 × 10^6,
x_t > 49 in.



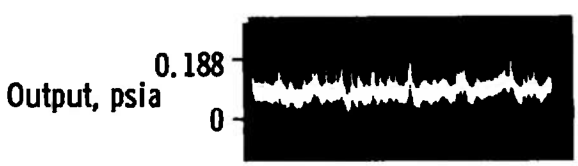
c. Approximate Beginning of
Transition (Profile A),
(Re/in.)$_\delta$ = 0.081 × 10^6, x_t > 49 in.



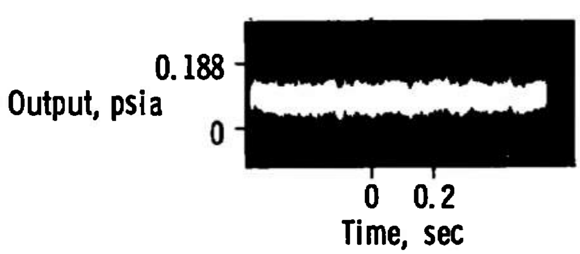
d. Approximate Beginning of
Transition (Profile A),
(Re/in.)$_\delta$ = 0.081 × 10^6, x_t > 49 in.



e. Peak Transitional Flow (Profile B),
(Re/in.)$_\delta$ = 0.11 × 10^6, $x_t \approx$ 45 in.



f. Turbulent Flow (Profile C),
(Re/in.) δ = 0.25 × 10^6, $x_t \approx$ 45 in.



g. Fully Developed Turbulent Flow (Profile D),
(Re/in.)$_\delta$ = 0.64 × 10^6, $x_t \approx$ 9 in.

Fig. 14 Oscilloscope Record of Microphone Output (Pressure Fluctuation) with Laminar, Transitional, and Turbulent Flow, M_∞ = 3.0

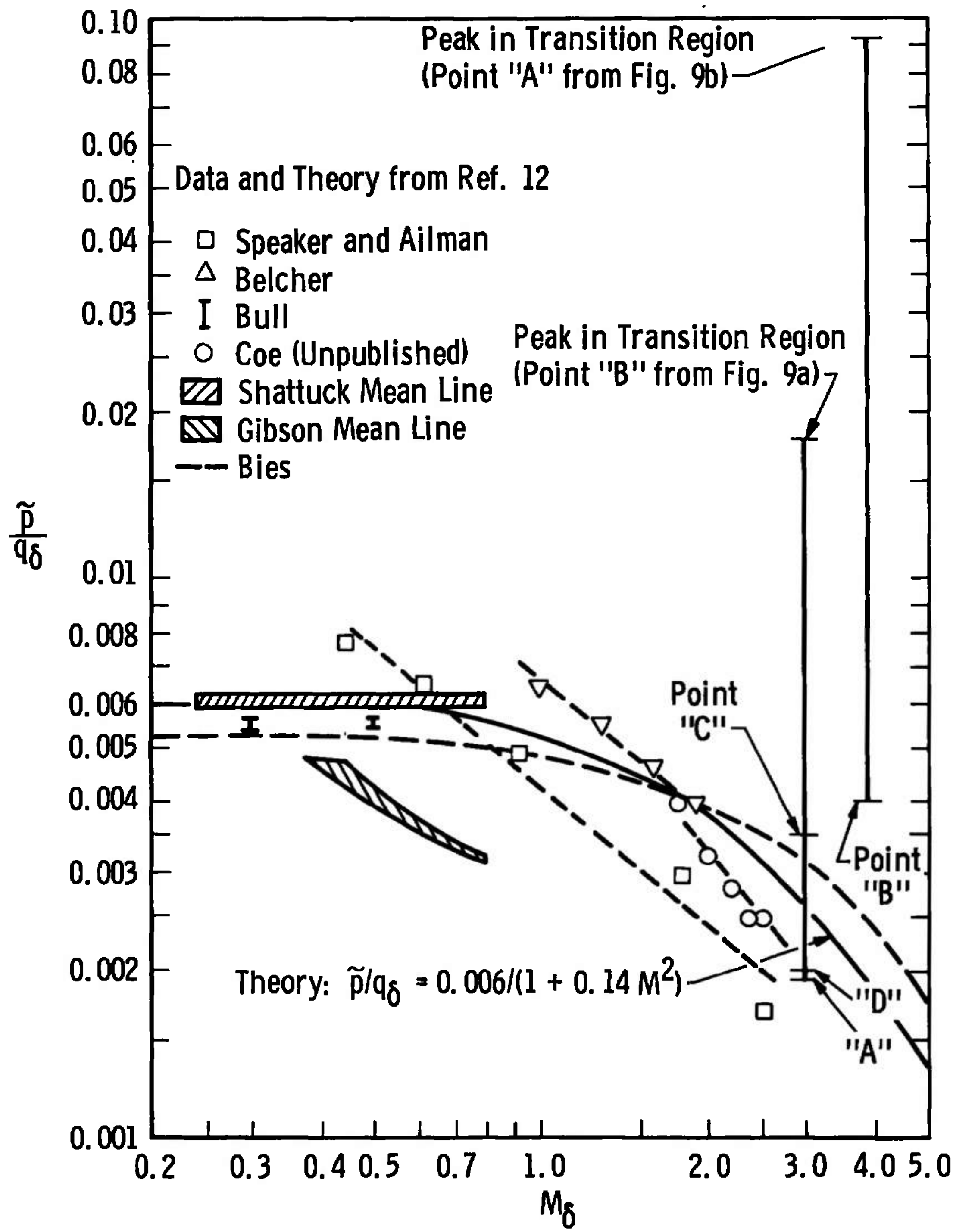


Fig. 15 Fluctuating Pressure Nondimensionalized by Dynamic Pressure versus Mach Number

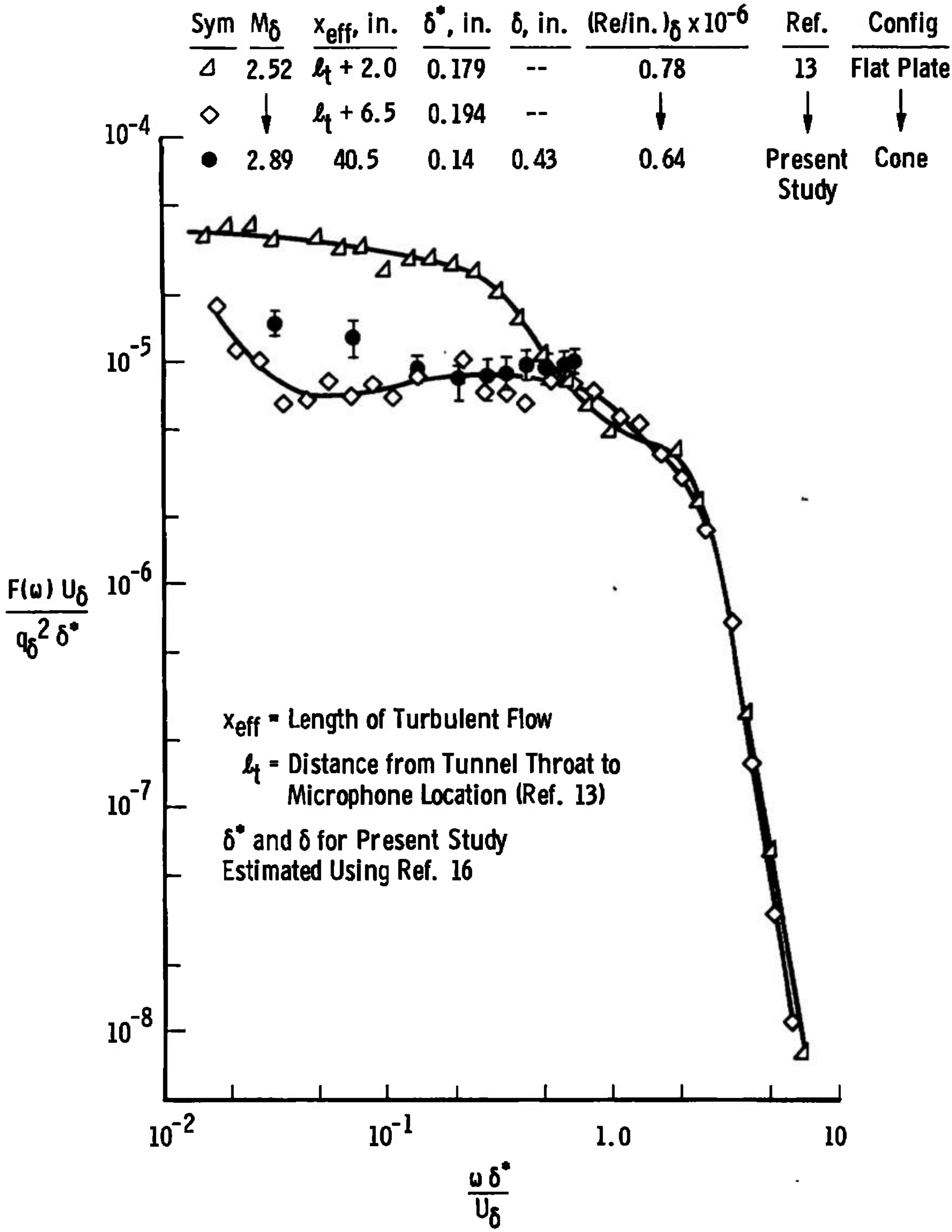


Fig. 16 Comparison of Pressure Fluctuation Spectra for Planar and Axisymmetric Flow

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13 ABSTRACT

Surface pressure fluctuations associated with transitional and turbulent boundary-layer flows on a sharp, slender cone at supersonic Mach numbers have been experimentally investigated in the AEDC-VKF Tunnel A 40- by 40-in. supersonic wind tunnel using a flush-mounted 0.25-in.-diam microphone. The results at Mach numbers 3 and 4 demonstrate the feasibility of locating microphones onboard wind tunnel test models to measure overall pressure fluctuations and power spectral distributions in transitional and fully developed turbulent flows. Transition Reynolds numbers determined using a surface microphone are compared with two other established methods of detection. Selected boundary-layer pressure fluctuation characteristics (power spectral density and root-mean-square values) and transition profiles are presented. Methods of data acquisition and analysis are discussed.

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